AD-A133 719 SPECAN (SPECTRAL ANALYSIS) - A PROGRAM IN ACSL FOR STOCHASTIC TIME SERIES ANALYSIS(U) AERONAUTICAL RESEARCH LABS MELBOURNE (AUSTRALIA) P H HALL JUL 83 1/1

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AR-002-964

AUSTRALIA

DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

AERONAUTICAL RESEARCH LABORATORIES

MELBOURNE, VICTORIA

Aerodynamics Technical Memorandum 352

SPECAN - A PROGRAM IN ACSL FOR STOCHASTIC TIME SERIES ANALYSIS

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Approved for Public Release

*Lieutenant P.H. Hall is an officer of the RAN and is on attachment to ARL.

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SPECAN - A PROGRAM IN ACSL FOR STOCHASTIC TIME SERIES ANALYSIS

by

P.H. HALL*

This document describes a computer program which uses Advanced Continuous Simulation Language (ACSL) on a DEC System-10 computer

SUMMARY

A program in ACSL for stochastic time series analysis ~~at~~ ARL has been documented in this Memorandum. The use of ACSL has considerably reduced programming effort and has provided the user with flexibility in the selection of various output options with different modes of presentation. An example of a spectral analysis of a discrete time series using SPECAN is also presented in this Memorandum.

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CONTENTS

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1. INTRODUCTION

"Time series analysis is now widely used in many branches of engineering, the physical sciences and economics. One important aspect of time series analysis is spectral analysis, which is concerned with the splitting up of time series into different frequency components. Applications of spectral analysis cover a wide range of problems, for example, the effect of wave oscillations on the vibration of ships and the influence of disturbances or noise on the performance of electrical guidance systems and chemical reactors" [1].

This Memorandum provides a documentation of a computer program which uses Advanced Continuous Simulation Language (ACSL*) for stochastic time series analysis on the ARL DEC System-1Ø computer. The formulae and terms used in the program are defined in section 2, while section 3 provides a description of available lag windows and discusses window closing and window carpentry techniques. An outline of the computer program SPECAN (SPECtral ANalysis) is provided in section 4, and an example of a spectral analysis of a discrete time series using SPECAN is presented in section 5.

2. DEFINITION OF FORMULAE AND TERMS USED IN SPECAN

All formulae and terms used in the program have been adapted from Jenkins and Watts [1].

2.1 Nyquist Frequency (f_N)

The Nyquist frequency is the highest frequency which can be detected with data sampled at intervals of Δ, and is determined by

$$f_N = 1/2\Delta \qquad (1)$$

2.2 Length of Data Record (T_R)

The length of the data record is simply defined by

$$T_R = N\Delta \qquad (2)$$

where N is the total number of data points in the record.

2.3 Test for White Noise

Situations often occur in practice where it is necessary to test whether an observed time series could be regarded as a product of a white noise process. If it is desirable to detect whether neighbouring

* Mitchell & Gauthier Associates, Inc.

points of the time series are correlated, then the application of 95% white noise confidence limits to the autocorrelation function estimate acts as a useful test for white noise.

$$\text{95\% WHITE NOISE CONFIDENCE LIMITS} \simeq \pm 2/\sqrt{N} \tag{3}$$

2.4 Sample Mean ($\bar{x}$)

The sample mean of the complete data series is defined by

$$\bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i \ . \tag{4}$$

2.5 Deviation (x_d)

The deviation from the mean of each data point is defined as

$$x_{d_i} = x_i - \bar{x} \ , \quad i = 1,\ldots.,N \ . \tag{5}$$

2.6 Autocovariance Function Estimate (acvf)

If the observations $x_1, x_2, \ldots.., x_N$ come from a discrete time series, the discrete time autocovariance function estimate is

$$c_{xx}(k) = \frac{1}{N} \sum_{i=1}^{N-k} (x_i - \bar{x})\,(x_{i+k} - \bar{x}) \tag{6}$$

which can be written

$$c_{xx}(k) = \frac{1}{N} \sum_{i=1}^{N-k} x_{d_i} . x_{d_{i+k}} \tag{7}$$

where $k = 0,1,\ldots.,N-1$.

2.7 Autocorrelation Function Estimate (acf)

As it is sometimes necessary to compare two or more time series with possibly different scales of measurement, estimates of the discrete time autocorrelation function are required rather than estimates of the acvf. Estimates of the acf may be obtained by dividing the above acvf estimates by the estimate of the variance, as follows

$$r_{xx}(k) = \frac{c_{xx}(k)}{c_{xx}(0)} \tag{8}$$

where $c_{xx}(k)$ is defined by equation (7) and the data variance corresponds to the acvf estimate for zero lag.

Note: For a stationary process, the acf is a function of the lag k only, and thus is essentially defined as a normalized acvf.

2.8 Smoothed Spectral Estimate (SSE)

Since the smoothed spectral estimate is an even function of frequency, it is only necessary to calculate it over the range $0 \leq f \leq f_N$. However, to preserve the Fourier transform relationship between the sample spectrum and the sample acvf, it is necessary to double the power associated with each frequency in that range. Hence the formula generally used to calculate the SSE is

$$\bar{C}_{xx}(f) = 2\Delta \left\{ c_{xx}(0) + 2 \sum_{k=1}^{L-1} c_{xx}(k) w(k) \cos 2\pi f k \Delta \right\} \tag{9}$$

where $0 \leq f \leq f_N$, L is the truncation lag number, and $w(k)$ is the weighting function of the lag window, while equation (7) need only be computed for $k \geq 0$.

For purposes of computation it is more efficient and convenient to assume $\Delta=1$, in which case all sets of data may be processed alike. Equation (9) may then take the form

$$\bar{C}_{xx}(f) = 2 \left\{ c_{xx}(0) + 2 \sum_{k+1}^{L-1} c_{xx}(k) w(k) \cos 2\pi f k \right\} \tag{10}$$

where $0 \leq f \leq 1/2$.

Note: If $\Delta \neq 1$, then the estimate obtained by equation (9) can be recovered from equation (10) by multiplying by Δ and plotting the estimate against $f\Delta$ instead of f.

2.9 Smoothed Spectral Density Estimate (SSDE)

If acf's are used instead of acvf's, the smoothed spectral density estimate is computed by the following expression.

$$\bar{R}_{xx}(f) = 2 \left\{ 1 + 2 \sum_{k=1}^{L-1} r_{xx}(k) w(k) \cos 2\pi f k \right\} \tag{11}$$

where $0 \leq f \leq 1/2$, and $r_{xx}(k)$ is defined by equation (8).

Jenkins and Watts recommend that, in order to obtain a more detailed plot of $\bar{R}_{xx}(f)$, the f values should be calculated at a spacing $1/(2F)$, where F is 2 or 3 times L. The final formula for digital computation of the SSDE is then

$$\bar{R}_{xx}(\ell) = 2\left\{1 + 2\sum_{k=1}^{L-1} r_{xx}(k)w(k)\cos\frac{\pi\ell k}{F}\right\} \tag{12}$$

where $\ell = 0,1,\ldots,F$.

3. LAG WINDOWS

The lag windows available in SPECAN are selected from those widely used in spectral analysis [1]. They are the Tukey, Parzen, Bartlett and Rectangular windows and are plotted in Figure 1, while their properties are summarized in Table 1. To perform window closing/carpentry exercises with SPECAN, the logical variables LOOP and FTSPLT must be set .TRUE. at run time. LOOP is defined in SPECAN and allows access to the window closing/carpentry logic, while FTSPLT is an ACSL parameter [2] which controls the ACSL overlay plot facility. Note that if FTSPLT is not set .TRUE., it defaults to .FALSE. such that only the results of the last resolution bandwidth in window closing, or the last lag window in window carpentry, will be available for plotting. It can be seen from Figure 2 how window closing/carpentry exercises are effected in the program.

As the topic of window carpentry and the effects of window shape on smoothing are well covered by Jenkins and Watts [1], only an informative summary of window closing and window carpentry is presented in this Memorandum. However, it is important to note that the critical decision in the design of a spectral analysis is the choice of window resolution bandwidth - not the choice of window shape - as will be seen by examining the example presented in section 5.

3.1 Window Closing

The main objective of window closing is to aid the physical insight in the process of estimating and interpreting spectra. It involves computing smoothed spectral estimates, initially with a wide resolution bandwidth, and then using progressively smaller bandwidths, such that the shape of the spectrum is allowed to evolve. The initial choice of a wide resolution bandwidth will usually conceal a certain amount of detail in the spectrum. More significant detail can be studied as the bandwidth is reduced until an optimum condition has been achieved where the resolution bandwidth of the window is less than the smallest significant detail in the spectrum.

Practical problems of interpretation may arise due to instability of the estimates [1], however it is possible to distinguish between three types of situation which may occur in practice:

(i) It is sometimes possible to narrow the bandwidth sufficiently to reveal most of the significant detail without incurring instability.

(ii) Sometimes it is clear that in no sense is the spectrum converging to a stable value.

(iii) A situation which usually falls somewhere between (i) and (ii).

These situations are all characterized by a tendency for the estimates to converge initially, but then to diverge due to instability before definite conclusions can be drawn.

When performing window closing exercises with SPECAN, the number of resolution bandwidths, MN, desired by the user should be set in the nominated data file. As the SSDE for each resolution bandwidth is computed, MN is reduced by one, until MN=0, at which stage the program will terminate.

3.2 Window Carpentry

Window carpentry relates to the design of the window which is to be used in the analysis, and therefore is of some importance, albeit secondary to window closing, as is shown empirically in Jenkins and Watts [1].

Briefly, Jenkins and Watts state that:

(i) Tukey and Parzen windows give comparable but superior results to the Bartlett window.

(ii) Parzen window has smaller sidelobe effects than the Tukey and Bartlett windows, but requires more autocovariances to achieve a given bandwidth. This means that the spectral estimate will settle down to a steady value more quickly by using a Tukey window rather than a Parzen window.

(iii) The Rectangular window performs badly by exhibiting much larger sidelobe effects than any of the Bartlett, Tukey or Parzen windows, and therefore its use is not recommended.

Note: The effect of sidelobes is to permit values of the power spectrum at frequencies distant from f to make large contributions to the bias at the frequency f, creating an effect known as "leakage".

When performing window carpentry exercises with SPECAN, MN must be set to unity in the nominated data file as only one resolution bandwidth is being examined.

4. SPECTRAL ANALYSIS PROGRAM - SPECAN

The program is designed for use on the ARL DEC System-10 computer and is structured so that the majority of computations are performed in FORTRAN subroutines called by the main program, SPECAN.CSL. The program layout therefore reduces the time required by the ACSL translator and allows independent access to the spectral analysis equations in the subroutines without the need to re-translate and then re-compile the main program. The dialogue for translating the main program, compiling and loading to obtain the run version of SPECAN (at the teletype terminal) is provided in Appendix A.

The Fourier Transform is evaluated in this program by the Jenkins and Watts finite difference algorithm [1 (app.7.1], not the Fast Fourier Transform algorithm.

4.1 Main Program - SPECAN.CSL

The main program, SPECAN.CSL (the .CSL extension is required by the ACSL translator), is written in ACSL [2] and therefore opens the ACSL library so that many alternatives for data output and plotting are readily made available without the need of any additional dedicated programming. A working knowledge of ACSL is assumed.

SPECAN.CSL acts as a co-ordinating centre for all data and computations by calling the subroutines GETDAT, MULCOR and AUSPEC. The Nyquist frequency, length of data record, and the 95% white noise confidence limits are calculated directly. A flowchart of SPECAN.CSL is shown in Figure 2.

4.2 Subroutine GETDAT

As the name implies, subroutine GETDAT "gets" the "data" by reading the input data file specified by the user, and transfers the data deck and desired lag window flags into arrays XN(I) and LW(J) respectively. GETDAT also calls subroutine FILTER and passes XN(I) for filtering as desired by the user.

The size of all data arrays is controlled by a set of DIMENSION statements in the main program, SPECAN.CSL. They are currently limited in size as follows:

Record of :	data deck	- XN(500)
	deviations	- XDEV(500)
	autocovariances	- CXX(500)
	autocorrelations	- RXX(500)
	window weights	- W(252)
	Smoothed Spectral Estimates	- CBXX(800)
	Smoothed Spectral Density Estimates	- RBXX(800)
	selected lag windows	- LW(4)

4.3 Subroutine FILTER

Called by GETDAT, FILTER is a dummy subroutine which allows the user to incorporate a number of filter options as may be desired. The required filter may then be selected by setting the parameter P in the data file to the appropriate index. P=1 is nominated as a default value and indicates that no filtering of the data is required and that all the data is to be used.

4.4 Subroutine MULCOR

MULCOR is based on the flowchart MULTICOR of Jenkins and Watts [1 (app. [illegible].3)]. The calculations of the sample mean and the deviations [illegible] the mea[illegible] se equations (4) and (5) respectively. The calculations [illegible] acv [illegible]stimator and the acf use equations (7) and (8) respectively.

4.5 Subroutines AUSPEC

AUSPEC is based on the flowchart AUTOSPEC of Jenkins and Watts [1 (app.7.1)]. The SSE and SSDE calculations use equations (10) and (12) respectively and the selected window is called according to the parameter LAGWIN.

4.6 Window Subroutines

Subroutines RECT, BART, TUKEY and PARZEN represent the Rectangular, Bartlett, Tukey and Parzen lag windows respectively. The weighting functions for these windows are as given in Table 1, a summary of lag window properties. The resolution bandwidth, degrees of freedom, and asymptotic variance are all calculated within the appropriate window subroutine.

4.7 Input Data Description

The following parameters are used as inputs and are made available to the main program by the subroutine GETDAT:

(a) N = total number of values in the data deck.

(b) NCOLS = number of columns of the data deck.

(c) MN = the number of resolution bandwidths to be used in windowing exercises. (It is suggested that MN=3 be used normally in window closing exercises in order to avoid confusion in the overlayed spectral plot. Set MN=1 for window carpentry exercises).

(d) MAXM = a constant which defines the maximum value of the truncation lag number, L. (MAXM is used in the switching logic in SPECAN to determine whether window closing or window carpentry exercises are to be performed once LOOP has been identified as .TRUE. In window closing exercises, L is successively halved, as can be seen in Figure 2, whereas in window carpentry exercises, L remains constant and equal to MAXM. It is recommended that the initial value of MAXM be chosen to be approximately N/4, noting that SPECAN requires MAXM to be a multiple of 2^n if MN = n+1, where n is an integer).

(e) DELTA = sampling interval.

(f) NF = the number of frequency values at which the spectral estimate is to be considered. (Normally 2-to-3 times MAXM [1]).

(g) P is a parameter specifying which filter, if any, is required. Default P=1 : no filtering, all data is used. (Filters to be supplied by users).

(h) LW(1), LW(2), LW(3), LW(4) : the lag window selection indices in order of use. (The windows are selected according to the parameter LAGWIN in the main program, as follows:

LAGWIN = LW(J), J=1,....,4
where LW(J) = 1 : Parzen window
LW(J) = 2 : Tukey window
LW(J) = 3 : Bartlett window
LW(J) = 4 : Rectangular window).

For example:-

(i) 1 Ø Ø Ø : window closing (MN>1) using Parzen window; no window carpentry.
ie. LAGWIN = LW(1) = 1.

(ii) 4 1 3 Ø : window closing (MN>1) using Rectangular window; or window carpentry (MN =1) between Rectangular, Parzen and Bartlett windows.
ie. LAGWIN = LW(1) = 4
= LW(2) = 1
= LW(3) = 3.

(iii) Ø 2 3 4 : LAGWIN = LW(1) = Ø, is a run termination condition as no lag window has been specified for first use. (Note that LAGWIN = LW(J) $\leq$ Ø and LAGWIN = LW(J) > 4 are general termination conditions).

(i) XN(1), XN(2), ... , XN(N): the data deck. Great care should be taken to avoid data errors as the spectrum can be quite sensitive to them.

4.8 Output Data Description

Important statistical information and select data parameters are automatically printed into the ACSL print file FOR2Ø.DAT, providing an echo-check of N,MN,MAXM,DELTA,NF,P and LAGWIN, as well as recording the following information:

(a) XMEAN = the data mean, $\bar{x}$, as calculated by equation (4).

(b) CXX(1) = the data variance for zero lag, $c_{xx}(\emptyset)$, as calculated by equation (6).

(c) FN = the Nyquist frequency, f_N, as calculated by equation (1).

(d) TR = the total length of the data record, T_R, as calculated by equation (2).

(e) BWIDTH = the resolution bandwidth, as defined in Table 1.

(f) DOF = the degrees of freedom, as defined in Table 1.

(g) AV = the asymptotic variance, as defined in Table 1.

(h) UWNL = the Upper White Noise Limit, corresponding to the 95% white noise upper limit, as calculated by equation (3).

(i) L = the truncation lag number for the respective resolution bandwidth.

Additional output may be selected at run-drive time by ACSL commands [2] provide one or more combinations of the following output possibilities:

(i) data printout and plot (XT versus DATUM, with or without XMEAN overlayed);

(ii) deviation printout and plot (XTDEV versus DATUM);

(iii) acvf estimate and plot (CXXK versus K);

(iv) acf estimate and plot (RXXK versus K, with or without the 95% white noise confidence limits overlayed);

(v) lag window weighting printout and plot (WK versus K) for individual windows or for window carpentry;

(vi) SSE printout and plot or log plot (CBXXF versus F);

(vii) SSDE printout and plot or log plot (RBXXF versus F);

(viii) options (vi) and (vii) may be plotted as individual plots or overlayed for window closing using several bandwidths.

The above options are the most commonly used [1]. However, the use of ACSL provides the user with a wide range of output options and modes of presentation, which are not normally available without considerable additional dedicated programming. Plots which are requested are automatically plotted into the ACSL plot file, FOR22.DAT.

4.9 Validation Test

In order to attain a reasonable level of user confidence in the program, a suitable practical example given in Jenkins and Watts [1], namely the spectral analysis of the batch data, was used as a test case to validate SPECAN. The results obtained from SPECAN agreed extremely well with those provided in Jenkins and Watts.

5. AN EXAMPLE OF A SPECTRAL ANALYSIS USING SPECAN

The following example is a brief spectral analysis of some aircraft vibration test data and is presented here in order to illustrate the use and scope of SPECAN. Evaluation and interpretation of the results obtained is limited to that which is considered necessary to describe certain characteristics of SPECAN and ACSL.

The data for this analysis arose from accelerometers responding to a bonker rocket firing to port with 200 lb thrust for 50 msec. The accelerometers were mounted on the aircraft fin and rudder, while the bonker rocket was mounted at the rudder horn balance. The data was recorded at intervals of 20 msec, and therefore represents an example of a discrete time series as values were only obtained at specific intervals of time. The input data file AVT.DAT for the preliminary analysis is included in Appendix B.

5.1 Preliminary Analysis

By choosing the input data values with careful regard to section 4.7, it is possible to conduct a complete preliminary analysis with one run of SPECAN. The run-drive commands for the preliminary analysis are listed in Appendix B.

5.1.1 Data

Figure 3 illustrates the time series of the aircraft vibration test data as generated by SPECAN, with the data mean shown overlayed. As no obvious trends or periodicities were revealed and the time series appears reasonably uniform about the mean, the data is assumed to be representative of a stationary time series and filtering may be considered unnecessary.

5.1.2 Pilot Spectrum

An immediate consequence of the stationarity assumption above is that both the acvf and the acf are functions of only the lag [1]. It therefore makes little difference which of the two functions is used to determine the spectrum, as the acf is simply a normalized acvf, as defined in section 2.7. The acf is used here as an intermediate step in the estimation of the spectral density function, and also as a guide for designing a spectral analysis.

As N=250 data points, the initial value of MAXM was chosen as 60 by the relationship recommended in section 4.7(d), hence the acf estimate was computed up to L=60 lags in SPECAN to achieve the pilot spectrum shown in Figure 4. Note that the spectral density has been plotted on a logarithmic scale. The Tukey lag window was used, and NF was chosen as 150 in accordance with section 4.7(f).

The bandwidth and 80% confidence interval shown on the pilot spectrum constitute a pair of "tolerance limits". The conversion from degrees of freedom to confidence interval is explained by Jenkins and Watts [1], and the conversion graph from that reference is presented as Figure 5.

Important points to note from Figure 4 and the computer print-out for the preliminary analysis, which is included in Appendix B, are that:

(i) the AV is quite large (0.180), which suggests that some of the smaller peaks may be spurious;

(ii) The DOF is small (11), such that the 80% confidence interval is quite wide, indicating that the large peaks are real, while the validity of the others is questionable;

(iii) BWIDTH is quite small (0.0222 cps) with respect to the important detail in the spectrum, indicating poor stability or instability.

5.1.3 Sample Autocorrelation Function

The sample acf for the aircraft vibration test data is plotted in Figure 6, while a computer print-out of the preliminary analysis in Appendix B lists the first 60 lags. The 95% white noise confidence limits are shown superimposed over the sample acf in Figure 7 as a test for white noise. For the window closing exercise, the truncation lag numbers, L, of 8, 16 and 32 have been chosen, where MAXM = 32; noting the discussion in section 4.7(d).

5.2 Smoothed Spectral Density Estimates

The SSDE were computed while the Tukey window was closed through the selected values of L. They are plotted together in Figure 8 by using the ACSL FTSPLT facility. The window resolution bandwidth and 80% confidence intervals are shown for each truncation lag number. A computer print-out of the results from SPECAN is included in Appendix B. The number of frequency values, NF, was chosen as 80 in accordance with section 4.7(f), so that for this run of SPECAN the following input parameters were adjusted:

(i) in AVT.DAT : MAXM = 32 , NF = 80

(ii) at run-time : FTSPLT = .T.
LOOP = .T.
CINT = 0.02.

Note: CINT is the ACSL communication interval parameter [2] and is set to the default value of 1.0. SPECAN is written such that if the sampling interval of the data, DELTA, is not equal to unity, than CINT must be set at run-time to be equal to DELTA, otherwise the run will be aborted and an error message will be displayed, as shown in Figure 2.

5.3 Interpretation of the Smoothed Spectral Density Estimates

5.3.1 Fidelity

From an inspection of Figure 8, it is clear that the resolution bandwidth corresponding to the estimate for L=8 is too wide to reveal all the detail in the spectrum, while the estimate for L=16 tends to under-estimate the peaks. If the width of a peak is measured by the distance between the half-power points [1], it can be seen in Figure 8 that the resolution bandwidth for MAXM = L = 32 is slightly less than the width of the narrowest peak, and therefore high fidelity is implied.

5.3.2 Stability

The variance of the estimates is an indication of stability. The variance decreases with increasing DOF (Figure 5) while the DOF in turn increases with the number of samples, N (Table 1). On the other hand, DOF decreases with increasing lag number, L. This contrasts with the resolution bandwidth, in section 5.3.1 above, which decreases with increasing L. Thus the choice of the truncation lag number reflects a compromise between Fidelity and Stability.

Note: As the SSDE for L=32 is relatively smooth and exhibits high fidelity and good stability, there appears to be no benefit in closing the Tukey window any further.

5.3.3 Resolution

An indication of good resolution is the fact that the resolution bandwidth for L=32, using the Tukey window, is slightly less than the width of the narrowest important peak in the spectrum. In general, high fidelity implies good resolution.

5.3.4 Bias

Bias is a measure of the offset distortion of the smoothed spectral estimate from the true spectrum. The total error in the spectral estimate is a combination of the variance of the estimate and the bias error. While variance may be decreased (and stability increased) by increasing the resolution bandwidth (decreasing L), this has the effect of increasing bias. A compromise is therefore required, keeping in mind also the requirement for good resolution (and fidelity) discussed above. The topic of bias is more fully covered in Jenkins and Watts [1].

5.3.5 Aliasing

As the topic of aliasing with respect to spectral analysis is adequately discussed by Jenkins and Watts [1] and other authors, such as Kanasewich [3], and Bendat and Piersol [4], it will be suffice to say that inspection of Figure 8 does not reveal any detail to suggest the presence or possibility of aliasing.

5.3.6 Frequency Limit

The highest frequency which may be reliably detected corresponds to the Nyquist Frequency.

5.4 Example of Window Carpentry

Recall from section 3.2 that the Tukey and Parzen windows are comparable. It can be shown in a similar way to the following comparison, that these windows have very similar performances. For this reason, and because results from the Tukey window have already been illustrated in Figure 8, the Tukey window has been omitted from the following window carpentry example.

Using the data of the aircraft vibration test, the SSDE's were computed for the Rectangular, Bartlett and Parzen windows, and are plotted together in Figure 9. It is readily seen that the Rectangular window performs badly by exhibiting much greater instability characteristics than either the Bartlett or Parzen windows, which display reasonable shapes and have similar performances.

When comparing the results obtained in window closing (Figure 8) against those in window carpentry (Figure 9), it is necessary to emphasize that it is the choice of window resolution bandwidth - not the choice of window shape - that is the important question in the design of a spectral analysis. A computer printout containing the important information associated with Figure 9 is included in Appendix B.

5.5 Summary

A spectral analysis of data provided from an aircraft vibration test has been conducted as an example in the use of SPECAN. Filtering was considered unnecessary as no trends or periodicities were detected in the data. The pilot spectrum, obtained as a preliminary analysis using a truncation lag number of 60, exhibited high fidelity but displayed signs of instability. The sample acf was examined and new truncation points selected such that MAXM = 32 was used. The Tukey lag window was then closed over the SSDE, resulting in the estimate corresponding to L=32 being identified as possessing high fidelity, good resolution, good stability, low variance and reasonably small bias.

Window carpentry was illustrated and the importance of choosing the correct resolution bandwidth (truncation lag number), rather than the window shape, was emphasized. The Rectangular window was shown to be unsuitable for this analysis because of its instability characteristics.

6. CONCLUSION

A program in ACSL, which has been written to perform the analysis of stochastic time series on the ARL DEC System-10 computer, has been documented in this Memorandum. The program has been based on the text of Jenkins and Watts, and has been previously validated by using an example provided therein. An example of a spectral analysis using the program has been presented. The use of ACSL requires little programming effort and provides the user with flexibility in selecting various output options with different modes of presentation.

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APPENDIX A

DIALOGUE FOR LOADING SPECAN AT TELETYPE TERMINAL

To obtain a run version of SPECAN, the procedure illustrated below should be followed when using the teletype terminal. Note that the user subroutines are grouped together in the file SPECTL.SUB.

```
.RU MUS:ACSL


*SPECAN

ACSL MODEL FILE: SPECAN.CSL
   LIST ON FILE: SPECAN.LST
   COMPILE FROM: SPECAN.FOR
LIST OPTNS USED: ET

END OF EXECUTION
CPU TIME: 16.20 ELAPSED TIME: 56.82
EXIT

.COM SPECAN
FORTRAN: SPECAN
MAIN.
.BLOCK
ZZSIML
ZZDERV

.COM SPECTL.SUB
FORTRAN: SPECTL
GETDAT
FILTER
MULCOR
AUSPEC
RECT
BART
TUKEY
PARZEN

.LOAD SPECAN,SPECTL,MUS:CAPPLT,MUS:ACSLIB/SEARCH
LINK:   Loading

EXIT

.SAVE
SPECAN saved
```

APPENDIX B

SPECTRAL ANALYSIS OF AIRCRAFT VIBRATION TEST DATA: INPUT AND OUTPUT DATA

SECTION

B.1 Data file AVT.DAT for preliminary analysis

```
250     : NUMBER OF DATA POINTS
10      : NUMBER OF COLUMNS IN DATA TABLE
1       : NUMBER OF BANDWIDTHS
60      : MAXIMUM VALUE OF TRUNCATION LAG NUMBER
0.02    : SAMPLING INTERVAL
150     : NUMBER OF FREQUENCY POINTS
1       : FILTER TYPE
2 0 0 0 : LAG WINDOWS DESIRED (1ST., 2ND., 3RD., 4TH.)

DATA DECK:

29.0 30.0 32.0 21.0  2.5  6.5 25.0 38.0 46.0 43.0
26.5 28.5 32.0 45.0 40.0 37.5 33.0 27.0 20.0 14.5
 9.5 16.5 19.5 28.0 27.5 27.0 27.5 32.5 35.5 39.5
39.0 35.0 30.5 31.0 30.5 30.0 26.0 26.5 28.5 29.5
33.5 31.0 28.0 28.0 28.5 29.0 28.5 28.0 26.5 27.0
28.5 30.0 30.5 30.5 29.5 28.0 32.0 35.0 36.5 33.0
27.0 24.0 25.0 26.0 28.5 25.5 22.5 23.5 24.0 28.5
33.5 29.0 29.5 30.0 31.0 28.0 26.0 28.5 33.5 30.0
26.0 23.0 24.5 26.5 25.5 25.0 30.0 33.0 30.5 28.0
26.5 25.0 28.0 35.0 28.0 23.0 18.0 25.0 29.5 29.0
29.0 28.5 29.5 31.0 26.0 26.5 28.0 28.0 28.0 27.0
25.5 24.5 25.5 27.0 30.0 29.5 29.0 29.0 28.5 30.5
29.0 26.5 25.5 26.0 29.0 29.0 28.5 26.5 25.5 25.5
25.0 25.0 26.5 30.0 30.0 29.0 24.5 26.0 28.0 30.0
29.0 27.0 26.5 26.0 31.5 29.0 26.0 24.0 23.0 27.5
31.0 34.0 30.0 27.0 22.0 23.0 24.0 24.5 25.5 29.0
28.5 27.0 23.0 25.5 29.0 32.0 36.5 34.0 30.5 27.0
22.5 24.0 24.5 25.5 28.0 27.5 27.0 27.5 27.5 27.5
25.0 23.0 26.5 30.0 35.0 26.0 23.5 22.0 24.0 30.0
30.5 31.0 31.5 29.0 26.0 26.5 27.5 29.0 27.0 26.0
22.5 29.0 31.5 30.0 27.5 25.0 25.5 26.5 28.0 30.5
34.0 30.0 26.5 27.0 29.0 31.0 29.5 28.5 29.0 27.0
25.0 26.0 28.0 30.0 30.5 29.0 28.0 26.0 30.0 30.5
30.5 31.5 30.0 26.5 28.0 29.5 30.0 31.0 27.5 24.0
29.5 29.0 28.5 27.0 26.0 27.5 30.0 35.0 31.5 28.0
```

B.2 Run-drive commands for preliminary analysis

```
 RU SPECAN

ACSL>SET TITLE="AVT: PRELIMINARY ANALYSIS"

ACSL>PREPAR DATUM,XT,XMEAN,K,RXXK,UWNL,LWNL,F,RBXXF

ACSL>SET CINT=0.02

ACSL>START

%FRSOPN File was not found
Unit=1 DSK:FOR01.DAT/ACCESS=SEQIN/MODE=ASCII

Enter new file specs. End with an $(ALT)
*AVT.DAT$

ACSL>PRINT RXXK,DATUM,XT,F,RBXXF

ACSL>SET PRNPLT=.F.

ACSL>SET CALPLT=.T.

ACSL>SET TTLCPL=.F.

ACSL>SET DEFPLT=.T.

ACSL>PLOT "XAXIS"=DATUM,XMEAN,'HI'=50.0,'LO'=0.0

ACSL>SET DEFPLT=.F.

ACSL>PLOT 'XTAG'=" - TIME (SECS)",XT

ACSL>PLOT "XAXIS"=F, XTAG'=" (CPS) ",RBXXF,'LOG','LO'=0.07,'HI'=12.0

ACSL>SET XINCPL=6.0

ACSL>SET YINCPL=7.0

ACSL>SET NPCCPL=1

ACSL>PLOT "XAXIS"=K, XTAG'=" (LAG) ",'XHI'=60.0,RXXK,'LO'=-0.4,'HI'=1.0

ACSL>SET DEFPLT=.T.

ACSL>PLOT 'XHI'=60.0,UWNL,'LO'=-0.4,'HI'=1.0

ACSL>PLOT 'XHI'=60.0,LWNL,'LO'=-0.4,'HI'=1.0
```

```
ACSL>SET DEFPLT=.F.

ACSL>SET LINCPL=.F.

ACSL>SET SYMCPL=.T.

ACSL>PLOT 'XHI'=60.0,'XTAG'=" (LAG) ",RXXK,'LO'=-0.4,'HI'=1.0,'CHAR'="<"

ACSL>STOP

STOP

END OF EXECUTION
CPU TIME: 24.73 ELAPSED TIME: 11:21.58
EXIT
```

B.3 Results of preliminary analysis

An abbreviated version of the results from the preliminary analysis of the aircraft vibration test data is presented below. The relevant ACSL output file is FOR2Ø.DAT.

```
SET TITLE="AVT: PRELIMINARY ANALYSIS"
PREPAR DATUM,XT,XMEAN,K,RXXK,OWNL,LOWL,F,RBXXF
SET CINT=0.02
START

NUMBER OF DATA POINTS (N): 250
SAMPLING INTERVAL (DELTA): .02
MAXIMUM VALUE OF THE TRUNCATION LAG NUMBER (MAXM): 60
NUMBER OF FREQUENCY POINTS (NF): 150
FILTER TYPE SELECTED (P): 1
NYQUIST FREQUENCY (FN) FOR TRUE DELTA: 25.0 CPS
RECORD LENGTH (TR) OF DATA: 5.000
DATA MEAN (XMEAN): 28.1
DATA VARIANCE IE. ZERO LAG (CXX(0)): 21.651599
95% WHITE NOISE CONFIDENCE LIMITS ON ACF: +/-.1265

NUMBER OF BANDWIDTHS (MN): 1
LAG WINDOW SELECTED (LAGWIN): 2
BANDWIDTH (BWIDTH): .0222 CPS
DEGREES OF FREEDOM (DOF): 11.1
ASYMPTOTIC VARIANCE (AV): .1800
TRUNCATION POINT (L): 60

PRINT RXXK,DATUM,XT,F,RBXXF
```

LINE	RXXK	DATUM	XT	F	RBXXF
0	1.0000000	0.0200000	29.000000	0.	1.9825040
1	0.6776818	0.0400000	30.000000	0.0033333	1.8985490
2	0.1741039	0.0600000	32.000000	0.0066667	1.6651210
3	-0.1813204	0.0800000	21.000000	0.0100000	1.3338790
4	-0.2193142	0.1000000	2.5000000	0.0133333	0.9742779
5	-0.0822964	0.1200000	6.5000000	0.0166667	0.6482264
.					
.					
28	0.0141755	0.5800000	35.500000	0.0933333	0.7140836
29	-4.315E-04	0.6000000	39.500000	0.0966667	0.7190101
30	0.0030183	0.6200000	39.000000	0.1000000	0.7945594
31	0.0312460	0.6400000	35.000000	0.1033333	1.0529400
32	0.0455422	0.6600000	30.500000	0.1066667	1.6207240
.					
.					
60	0.0024028	1.2200000	27.000000	0.2000000	2.4568150
.					
.					
150	0.0024028	3.0200000	31.000000	0.5000001	0.2263552
.					
.					
248	0.0024028	4.9800000	31.500000	0.5000001	0.2263552
249	0.0024028	5.0000000	28.000000	0.5000001	0.2263552

```
SET PRNPLT=.F.
SET CALPLT=.T.
SET TTLCPL=.F.
SET DEFPLT=.T.
PLOT "XAXIS"=DATUM,XMEAN,'HI'=50.0,'LO'=0.0
SET DEFPLT=.F.
PLOT 'XTAG'=" - TIME (SECS)",XT
PLOT "XAXIS"=F,'XTAG'=" (CPS) ",RBXXF,'LOG','LO'=0.07,'HI'=12.0
SET XINCPL=6.0
SET YINCPL=7.0
SET NPCCPL=1
PLOT "XAXIS"=K,'XTAG'=" (LAG) ",'XHI'=60.0,RXXK,'LO'=-0.4,'HI'=1.0
SET DEFPLT=.T.
PLOT 'XHI'=60.0,UWNL,'LO'=-0.4,'HI'=1.0
PLOT 'XHI'=60.0,LWNL,'LO'=-0.4,'HI'=1.0
SET DEFPLT=.F.
SET LINCPL=.F.
SET SYMCPL=.T.
PLOT 'XHI'=60.0,'XTAG'=" (LAG) ",RXXK,'LO'=-0.4,'HI'=1.0,'CHAR'="<"
STOP
```

B.4 Results of window closing

The results of the window closing exercise in obtaining the smoothed spectral density estimates is presented below. The relevant ACSL output file is FOR2Ø.DAT. Note that output of the co-ordinates F and RBXXF has not been requested by either an OUTPUT or PRINT command and hence they have been suppressed.

```
SET TITLE="AVT: WINDOW CLOSING"
PREPAR F,RBXXF
SET CINT=0.02
SET FTSPLT=.T.
SET LOOP=.T.
SET ISTOP=8'
START

NUMBER OF DATA POINTS (N): 250
SAMPLING INTERVAL (DELTA):  .02
MAXIMUM VALUE OF THE TRUNCATION LAG NUMBER (MAXM):  32
NUMBER OF FREQUENCY POINTS (NF):  80
FILTER TYPE SELECTED (P): 1
NYQUIST FREQUENCY (FN) FOR TRUE DELTA: 25.0 CPS
RECORD LENGTH (TR) OF DATA:   5.000
DATA MEAN (XMEAN): 28.1
DATA VARIANCE IE. ZERO LAG (CXX(0)):  21.651599
95% WHITE NOISE CONFIDENCE LIMITS ON ACF: +/-.1265

NUMBER OF BANDWIDTHS (MN): 3
LAG WINDOW SELECTED (LAGWIN): 2
BANDWIDTH (BWIDTH): .0417 CPS
DEGREES OF FREEDOM (DOF): 20.8
ASYMPTOTIC VARIANCE (AV): .0960
TRUNCATION POINT (L):  32

NUMBER OF BANDWIDTHS (MN): 2
LAG WINDOW SELECTED (LAGWIN): 2
BANDWIDTH (BWIDTH): .0833 CPS
DEGREES OF FREEDOM (DOF): 41.7
ASYMPTOTIC VARIANCE (AV): .0480
TRUNCATION POINT (L):  16

NUMBER OF BANDWIDTHS (MN): 1
LAG WINDOW SELECTED (LAGWIN): 2
BANDWIDTH (BWIDTH): .1667 CPS
DEGREES OF FREEDOM (DOF): 83.3
ASYMPTOTIC VARIANCE (AV): .0240
TRUNCATION POINT (L):   8

SET PRNPLT=.F.
SET TTLCPL=.F.
SET CALPLT=.T.
PLOT "XAXIS"=F, XTAG =" (CPS) ",RBXXF,'LOG','LO'=0.07,'HI'=12.0
STOP
```

B.5 Results of window carpentry

The results of the window carpentry example discussed in section 5.4 are presented below. Comparison with the Tukey window can be handled by considering the results in Appendix B.4 with respect to those listed here. The relevant ACSL output file is FOR2Ø.DAT.

```
SET TITLE="AVT: WINDOW CARPENTRY"
PREPAR F,RBXXF
SET CINT=0.02
SET LOOP=.T.
SET FTSPLT=.T.
SET ISTOP=81
START

NUMBER OF DATA POINTS (N): 250
SAMPLING INTERVAL (DELTA):  .02
MAXIMUM VALUE OF THE TRUNCATION LAG NUMBER (MAXM):  32
NUMBER OF FREQUENCY POINTS (NF):  80
FILTER TYPE SELECTED (P): 1
NYQUIST FREQUENCY (FN) FOR TRUE DELTA: 25.0 CPS
RECORD LENGTH (TR) OF DATA:    5.000
DATA MEAN (XMEAN): 28.1
DATA VARIANCE IE. ZERO LAG (CXX(0)):  21.651599
95% WHITE NOISE CONFIDENCE LIMITS ON ACF: +/-.1265

NUMBER OF BANDWIDTHS (MN): 1
LAG WINDOW SELECTED (LAGWIN): 1
BANDWIDTH (BWIDTH): .0581 CPS
DEGREES OF FREEDOM (DOF): 29.0
ASYMPTOTIC VARIANCE (AV): .0690
TRUNCATION POINT (L):  32

NUMBER OF BANDWIDTHS (MN): 1
LAG WINDOW SELECTED (LAGWIN): 3
BANDWIDTH (BWIDTH): .0469 CPS
DEGREES OF FREEDOM (DOF): 23.4
ASYMPTOTIC VARIANCE (AV): .0853
TRUNCATION POINT (L):  32

NUMBER OF BANDWIDTHS (MN): 1
LAG WINDOW SELECTED (LAGWIN): 4
BANDWIDTH (BWIDTH): .0156 CPS
DEGREES OF FREEDOM (DOF):  7.8
ASYMPTOTIC VARIANCE (AV): .2560
TRUNCATION POINT (L):  32

SET PRNPLT=.F.
SET TTLCPL=.F.
SET CALPLT=.T.
PLOT "XAXIS"=F, XTAG =" (CPS) ",RBXXF,'LOG','LO'=0.07,'HI'=12.0
STOP
```

TABLE 1: Some common lag windows and their properties

WINDOW	LAGWIN	WEIGHTING FUNCTION	VARIANCE RATIO (AV)	DEGREES OF FREEDOM (DOF)	RESOLUTION BANDWIDTH (BWIDTH)
PARZEN	1	$w(k) = \begin{cases} 1 - 6\left(\frac{k}{L}\right)^2 + 6\left(\frac{\lvert k\rvert}{L}\right)^3, & \lvert k\rvert \leq L/2 \\ 2\left(1 - \frac{\lvert k\rvert}{L}\right)^3, & L/2 < \lvert k\rvert \leq L \\ \emptyset, & \lvert k\rvert > L \end{cases}$	$\frac{0.539L}{N}$	$\frac{3.71N}{L}$	$\frac{1.86}{L}$
TUKEY	2	$w(k) = \begin{cases} 1/2\left(1 + \cos\frac{\pi k}{L}\right), & \lvert k\rvert \leq L \\ \emptyset, & \lvert k\rvert > L \end{cases}$	$\frac{0.75L}{N}$	$\frac{8N}{3L}$	$\frac{4}{3L}$
BARTLETT	3	$w(k) = \begin{cases} 1 - \frac{\lvert k\rvert}{L}, & \lvert k\rvert \leq L \\ \emptyset, & \lvert k\rvert > L \end{cases}$	$\frac{2L}{3N}$	$\frac{3N}{L}$	$\frac{1.5}{L}$
RECTANG-ULAR	4	$w(k) = \begin{cases} 1, & \lvert k\rvert \leq L \\ \emptyset, & \lvert k\rvert > L \end{cases}$	$\frac{2L}{N}$	$\frac{N}{L}$	$\frac{0.5}{L}$

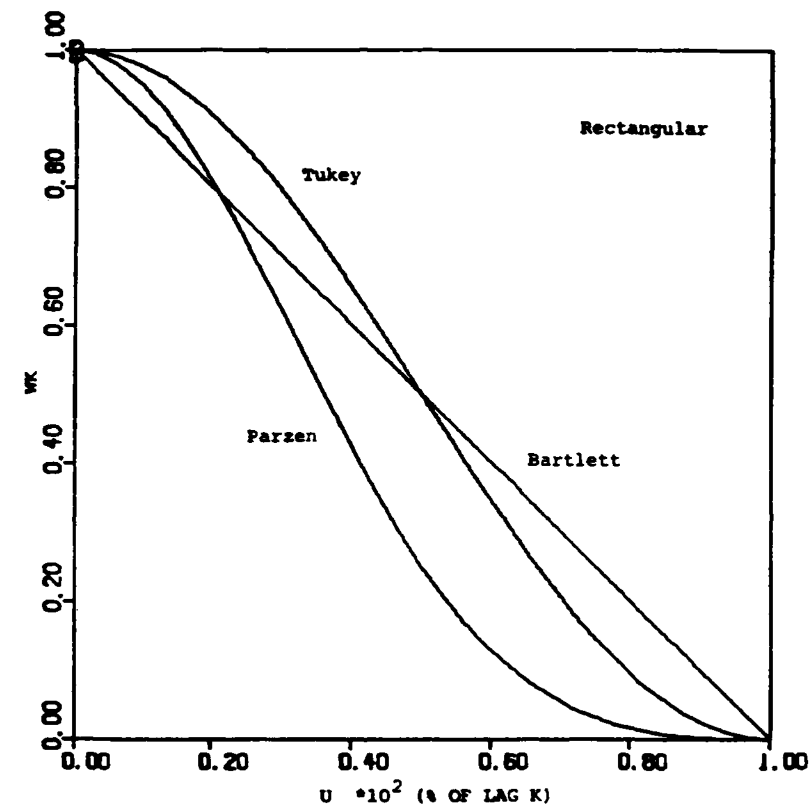

FIG. 1: Lag windows available in SPECAN

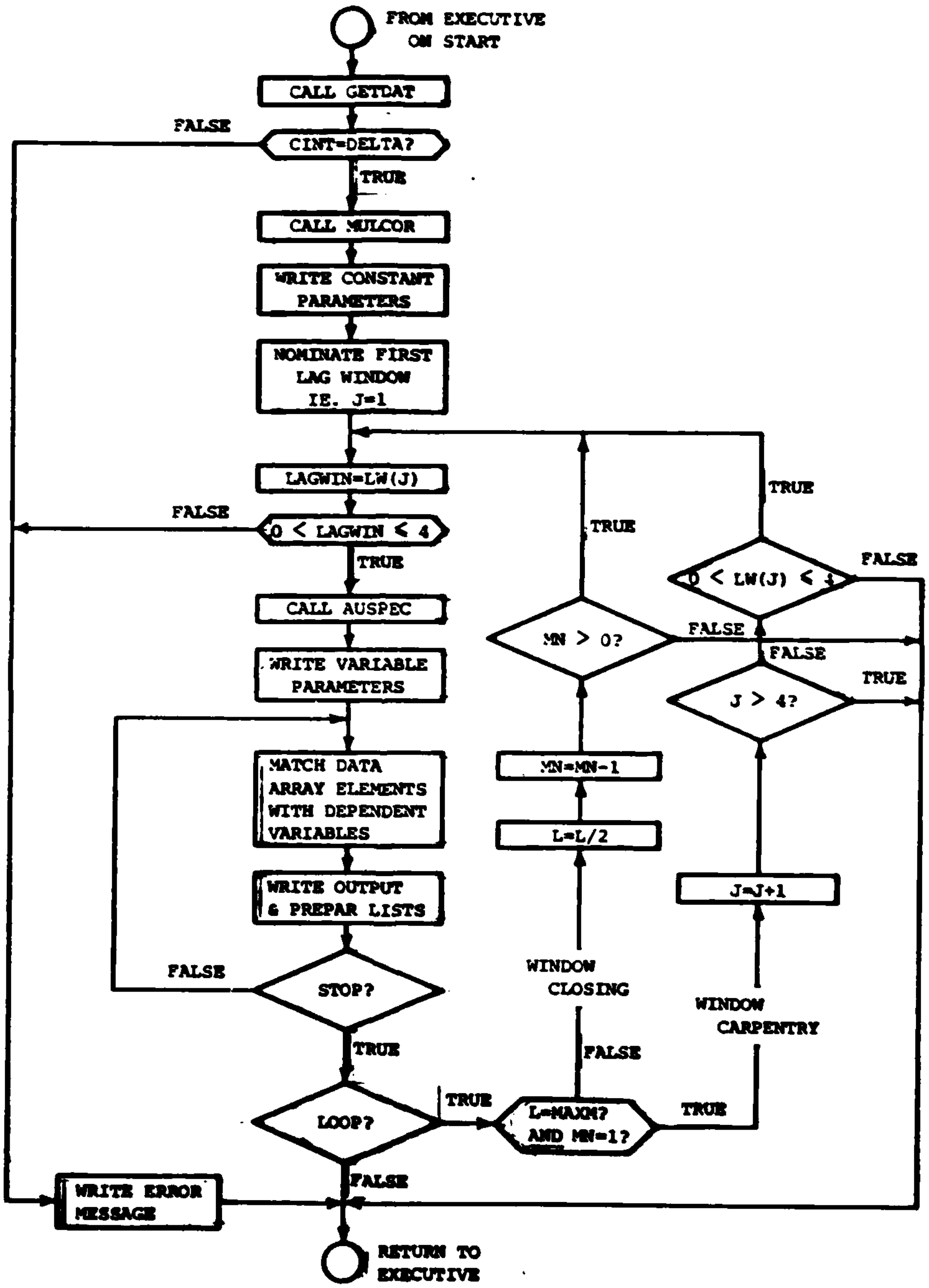

FIG. 2: Flowchart for SPECAN.CSL

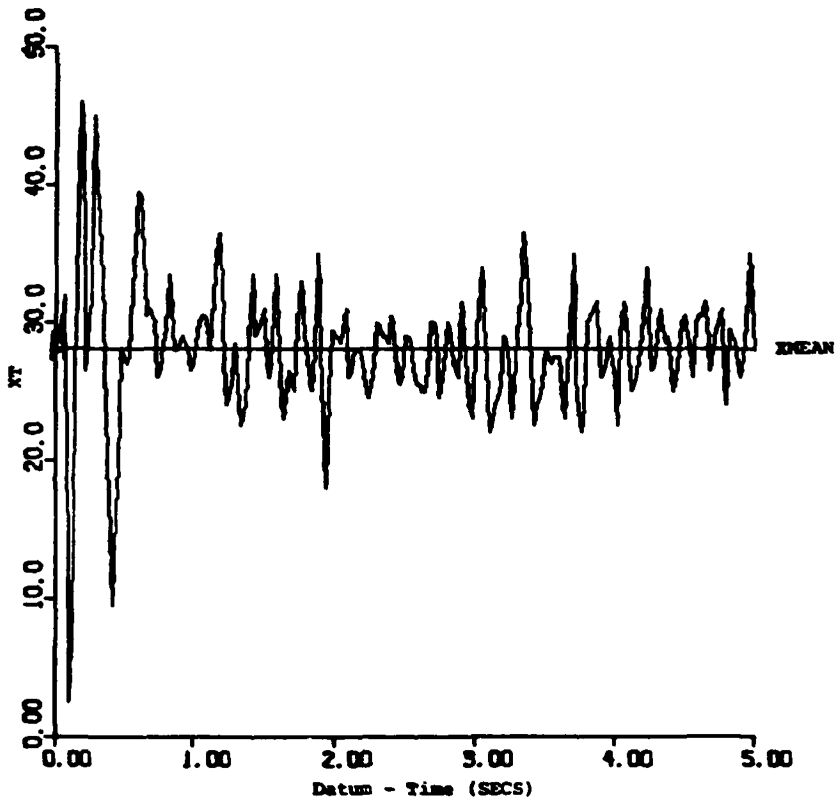

FIG. 3: Time history of the aircraft vibration test data.

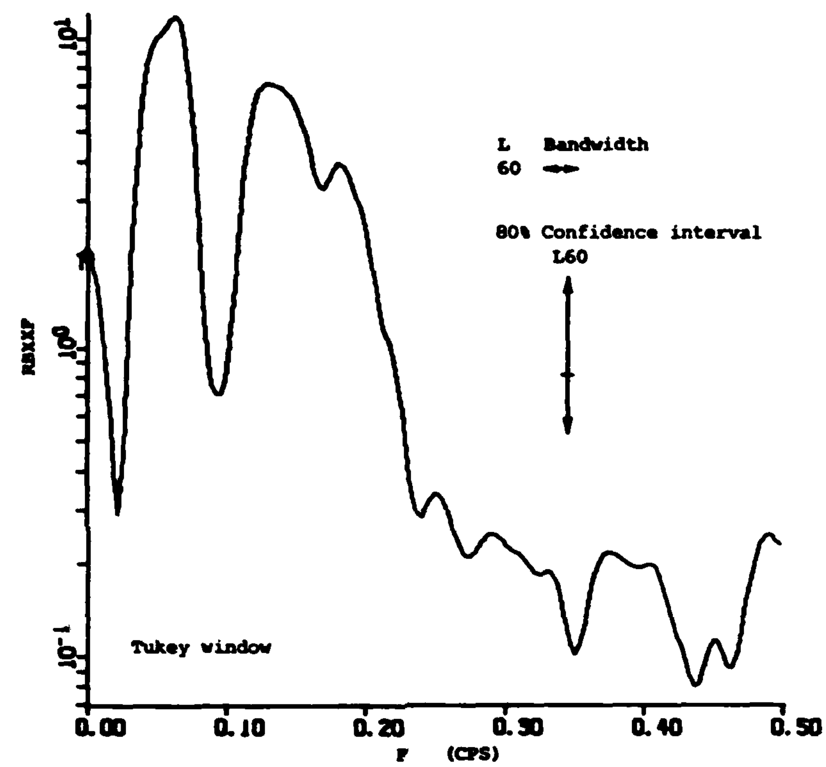

FIG. 4: Pilot spectrum for the aircraft vibration test data, using the Tukey lag window.

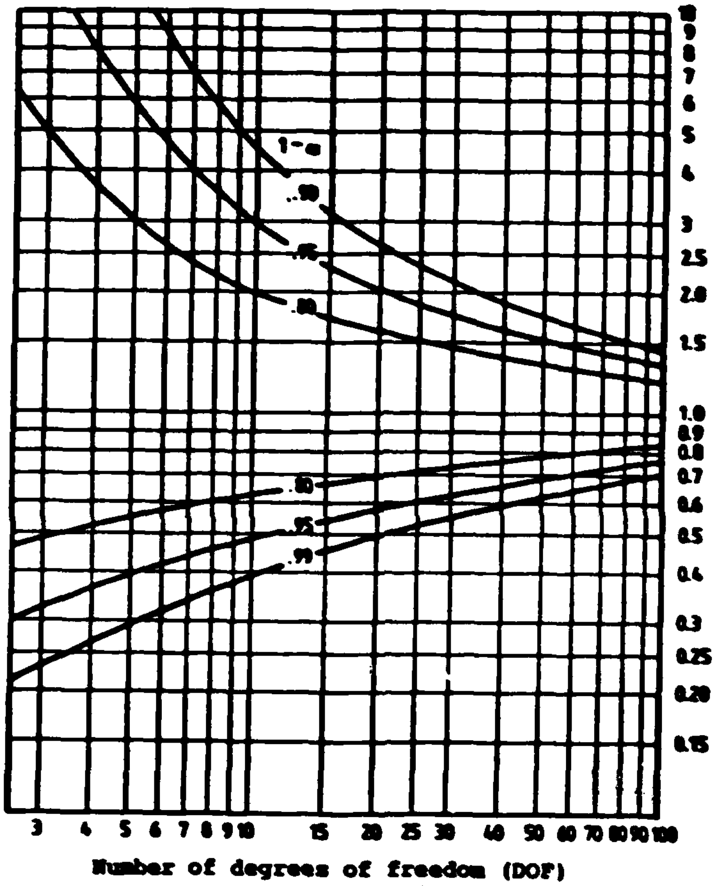

FIG. 5: Conversion plot to obtain confidence intervals for the smoothed spectral density estimate according to the number of degrees of freedom, for (1-α) = 0.80, 0.95, 0.99.

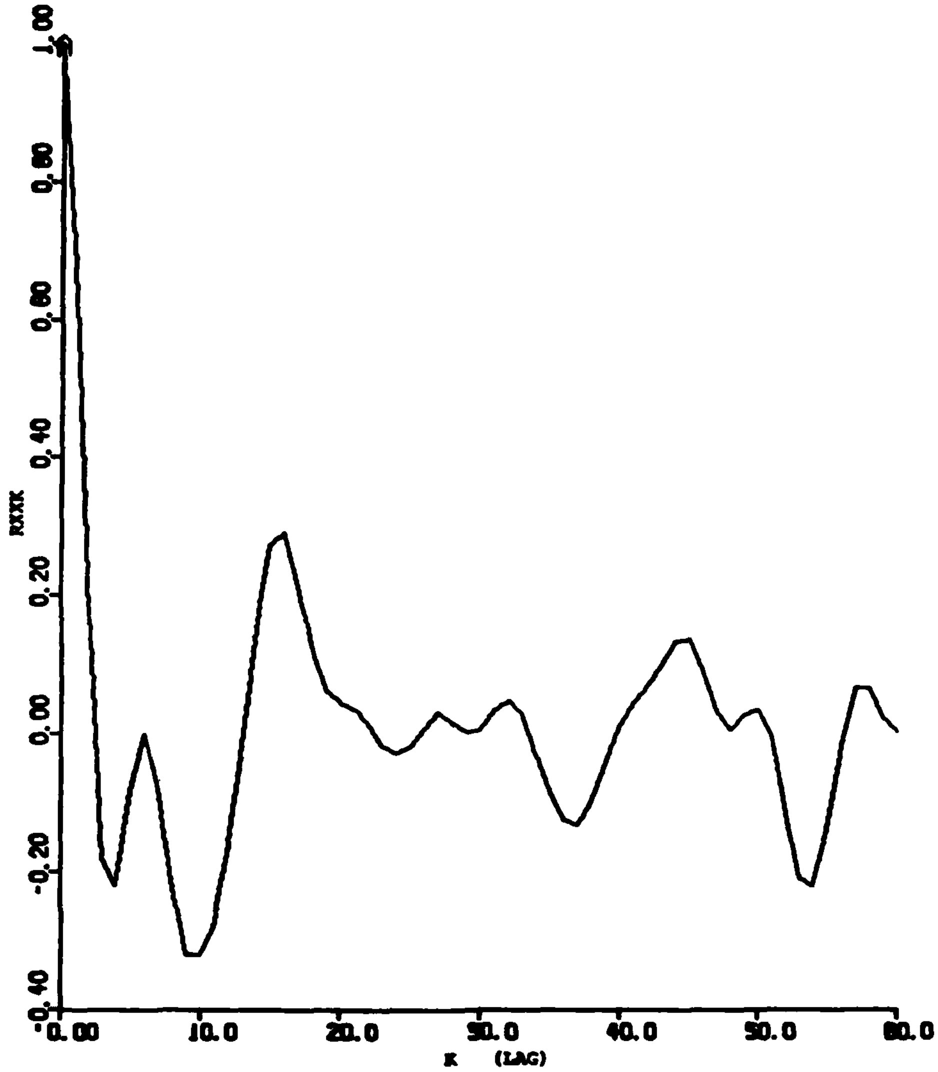

FIG. 6: Sample autocorrelation estimate for the aircraft vibration test data preliminary analysis.

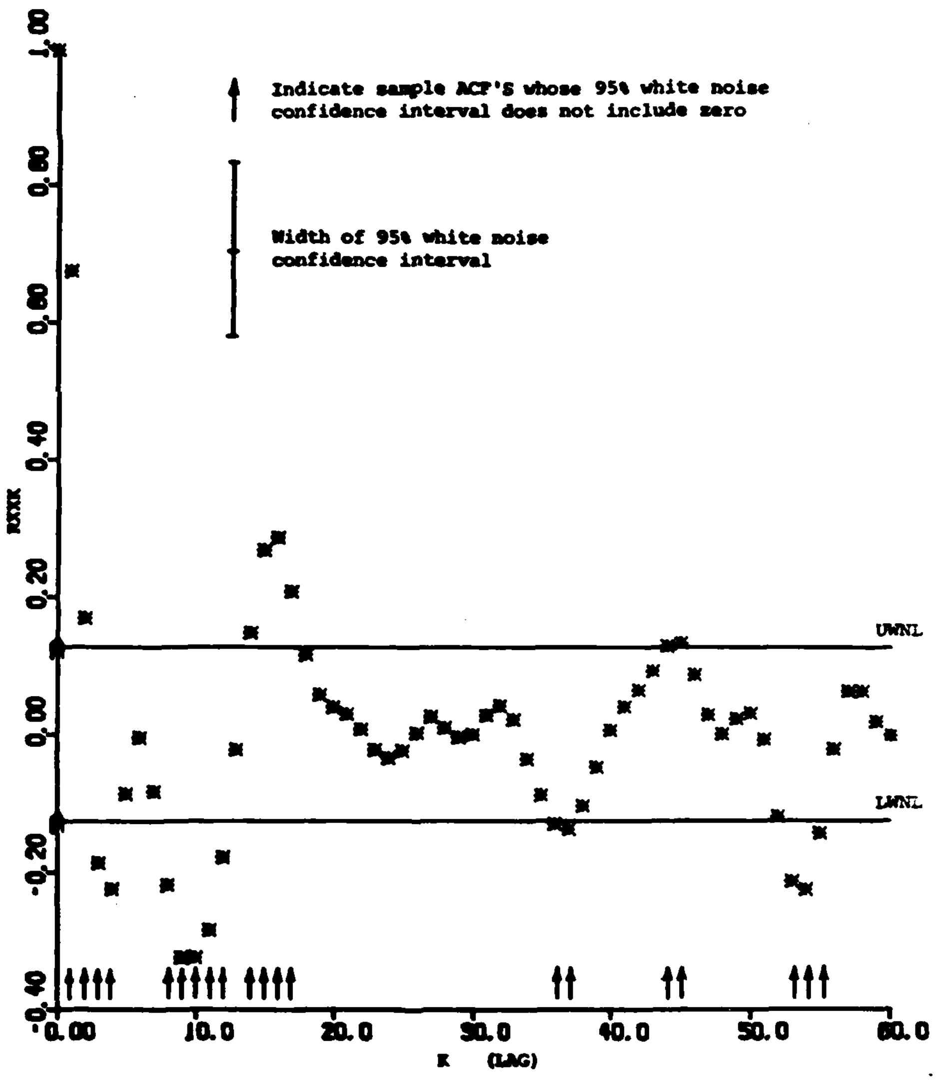

FIG. 7: Sample autocorrelation functions for the aircraft vibration test data sample, showing the 95% white noise confidence interval.

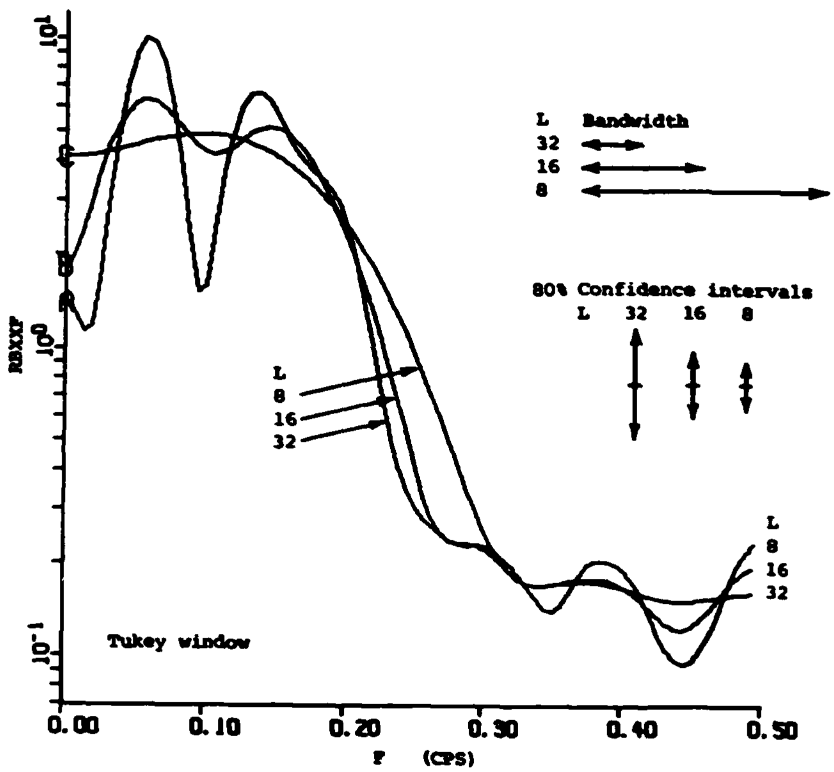

FIG. 8: Window closing to obtain smoothed spectral density estimates for the aircraft vibration test data, using the Tukey lag window.

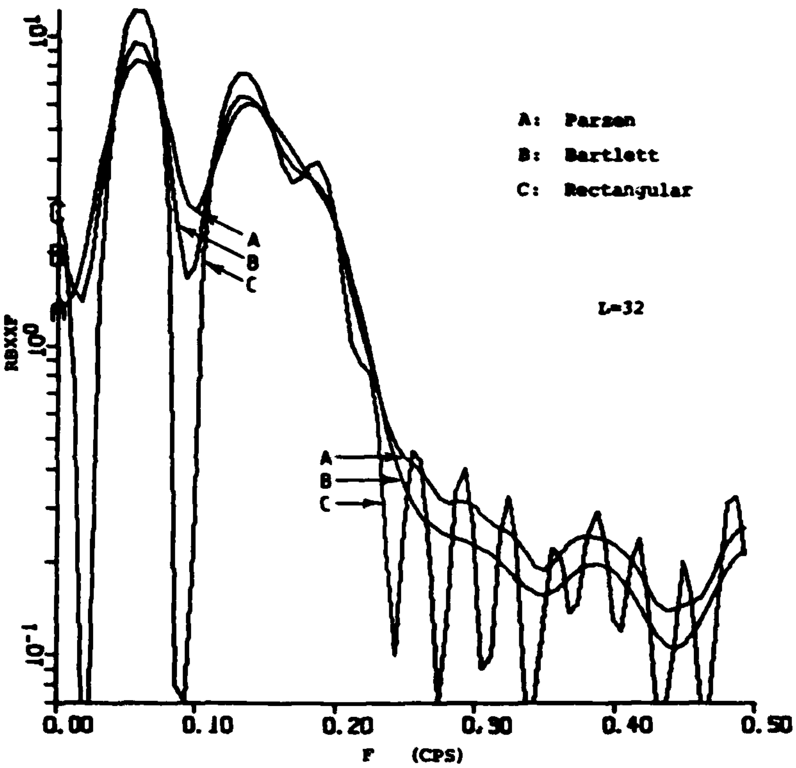

FIG. 9: Smoothed spectral density estimates of the aircraft vibration test data, illustrating window carpentry for L=32.

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Spectrum analysis Power spectra Stochastic processes Time series analysis Advanced Continuous Simulation Language (ACSL)	1201

16. Abstract

A program has been developed using Advanced Continuous Simulation Language for stochastic time series analysis. The program calculates the autocovariance and autocorrelation functions for a given discrete time series and combines them with selected lag window weighting functions to obtain power spectra. An example of a spectral analysis of a discrete time series using the program is presented.

PF 65

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16. Abstract (Contd)

17. Imprint

Aeronautical Research Laboratories, Melbourne.

18. Document Series and Number	19. Cost Code	20. Type of Report and Period Covered
Aerodynamics Technical Memorandum 352	52 7770	

21. Computer Programs Used

SPECAN.CSL - in ACSL, Level 7A

SPECTL.SUB - in Fortran

22. Establishment File Ref(s)

END

DATE
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11 83

D.